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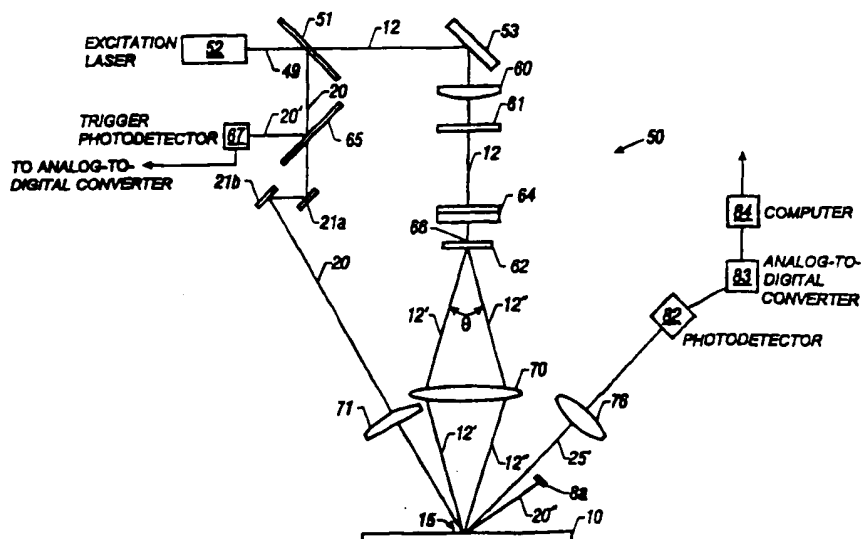
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(54) Title: IMPROVED METHOD AND APPARATUS FOR MEASURING THE CONCENTRATION OF IONS IMPLANTED IN SEMICONDUCTOR MATERIALS



(57) Abstract

A method and apparatus that determines a concentration of ions implanted in a material is described. The method includes the steps of: 1) generating at least two excitation laser sub-pulses and a probe pulse from a single pulse emitted from a laser; 2) irradiating a region of the material with a grating pattern formed by overlapping at least two excitation laser sub-pulses to initiate a time-dependent response in the region; 3) diffracting a probe laser pulse off the region to generate at least one time-dependent signal beam; 4) detecting at least one time-dependent signal beam to generate a signal waveform; and 5) processing the signal waveform to determine the concentration of ions implanted in the material.

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IMPROVED METHOD AND APPARATUS FOR MEASURING THE
CONCENTRATION OF IONS IMPLANTED IN
SEMICONDUCTOR MATERIALS

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Background

This invention relates to measuring the concentration of ions implanted in semiconductor materials.

10 Most microelectronic devices (e.g., microprocessors) include a series of thin insulating (e.g. oxide) and conducting (e.g., metal and polysilicon) films grown or deposited on a single-crystal silicon wafer. Both silicon wafers and polysilicon films are
15 implanted with ions during fabrication so that they exhibit a specified electrical conductance. For example, the silicon may be implanted to create regions that function as a "p" or "n" type semiconductor. After implantation, both silicon and polysilicon are annealed
20 under high temperatures to heal lattice damage that typically results from the implantation process.

The electrical conductance of silicon and polysilicon is strongly affected by three properties of the implanted ions: (1) atomic composition; (2)
25 implantation energy; and (3) ion concentration or dose. Silicon's electrical conductivity is particularly dependent on the concentration of the implanted ions. For example, silicon wafers are typically implanted with arsenic, argon, phosphorous, oxygen, or boron ions
30 ranging in concentration from 10^{12} - 10^{16} cm⁻³. These ions are typically implanted with energies ranging from a few keV to thousands of keV.

The performance of a completed microelectronic device depends critically on the electrical properties of
35 the silicon wafer and the overlying polysilicon films, and thus the properties of ions implanted in these

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materials are carefully monitored during fabrication. One property, called electrical sheet resistance, is measured by contacting a sample's surface with an electrical-testing instrument called a 4-point probe.

5 Electrical current flowing from one probe to another depends on the resistance of the material. Resistance, in turn, varies inversely with the concentration of implanted ions.

Ion concentration is also monitored using a
10 non-contact, optical method that excites and detects both a photothermal response and an electron-hole plasma within the silicon. To make this measurement, a first laser beam irradiates the silicon and is partially absorbed to generate either (or both) the electron-hole
15 plasma and photothermal response. These responses modify the reflectivity of the sample's surface and are measured with a second laser beam. This is partially reflected by the sample and then analyzed to estimate the concentration of the implanted ions.

20 Although used throughout the microelectronics industry to determine the concentration of implanted ions, both 4-point probes and instruments that measure optical reflectivity suffer disadvantages. 4-point probes necessarily contact the sample, and are therefore
25 destructive. This means that these instruments can only measure "monitor" wafers or regions of "product" wafers that lack functioning devices. In addition, 4-point probes can only measure annealed wafers. Optical-reflectivity instruments have a limited scope of
30 measurement and generate signals that are often difficult to interpret: they are therefore used primarily to determine whether or not a sample has been ion implanted with ions, rather than the actual concentration of the implanted ions.

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Summary

The method and apparatus described herein measure the concentration of ions implanted within a semiconducting material with a non-contact, laser-based technique called four-wave mixing (FWM). In the applications described herein, FWM is carried out with a single laser. This allows measurement of samples that have been difficult or impossible to measure with the two-laser systems described previously.

10 FWM initiates an optical response in a semiconducting material with two laser beams. These beams, which have wavelengths that are strongly absorbed by the sample, are overlapped in time and space on the sample's surface to form a grating pattern. Each laser beam includes pulses that typically have a duration of less than 1 nanosecond. Absorption of the pattern generates a time-dependent change in the sample's refractive index, resulting in a response that rapidly increases in amplitude and then decays away in a few nanoseconds. A third laser beam irradiates the grating pattern and is diffracted to form a fourth signal beam. The amplitude of the signal beam depends on the concentration of the ions implanted in the semiconductor material. This concentration can then be analyzed and used to control fabrication processes used to make microelectronic devices.

In one aspect, the invention provides a method that determines a concentration of ions implanted in a material. The method includes the steps of: 1) generating at least two excitation laser sub-pulses and a probe pulse from a single pulse emitted from a laser; 2) irradiating a region of the material with a grating pattern formed by overlapping at least two excitation laser sub-pulses to initiate a time-dependent response in the region; 3) diffracting a probe laser pulse off the

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region to generate at least one time-dependent signal beam; 4) detecting at least one time-dependent signal beam to generate a signal waveform; and 5) processing the signal waveform to determine the concentration of ions implanted in the material.

In another aspect, the method includes the step of generating a single laser pulse, and then passing the laser pulse through a diffracting mask to form at least two excitation sub-pulses and at least one probe pulse. Both excitation and probe pulses then irradiate the sample as described above to measure the concentration of ions implanted in the semiconductor. Here, a single pulse may function as both the excitation sub-pulse and the probe pulse (i.e., self diffraction).

In certain embodiments, the processing step described above includes determining a property of the signal waveform (e.g., an amplitude) and then processing the property to determine the concentration of ions implanted in the sample. The processing step may include comparing the property of the signal waveform to a database, e.g., a database that correlates properties of previously measured signal waveforms to concentrations of implanted ions. In other embodiments, the processing step includes analyzing the amplitude with a mathematical algorithm to determine the concentration of ions implanted in the material. The processing step can also include digitizing the signal waveform to generate a data set, and then determining the amplitude of the signal waveform at a point in time by selecting a value from the data set. In still other embodiments, the processing step includes determining an area covered by a plot of the signal waveform, and then comparing the area to a database similar to that described above.

The above-described method and apparatus determines the concentration of ions implanted in

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different types of host samples. These samples include semiconducting materials, such as silicon-containing (e.g. polysilicon) films, silicon wafers, and films and wafers containing gallium arsenide, aluminum gallium
5 arsenide, germanium, and derivatives and analogies thereof. Other samples that can be measured include ceramic materials, metals, and any other material that can be implanted with ions. The ion implanted in the material is typically an ion of an atom selected from the
10 group including arsenic, argon, boron, oxygen and phosphorous atoms.

The method of the invention is carried out with an apparatus that includes: 1) a single laser that generates an excitation laser pulse and a probe laser pulse; 2) a
15 first beam-delivery system that separates the excitation laser pulse into at least two sub-pulses and then irradiates a region of the material with a grating pattern formed by overlapping at least two sub-pulses; 3) a second beam-delivery system that delivers the probe
20 pulse to the sample such that it diffracts off the region to generate a time-dependent signal beam; 4) a photodetector that detects the time-dependent signal beam to generate a signal waveform; and 5) a processor that processes the signal waveform to determine the
25 concentration of ions implanted in the material.

In typical embodiments, the first beam-delivery system includes a diffracting mask (e.g., a phase or amplitude mask) that separates the excitation laser pulse into at least two sub-pulses. The processor is typically
30 a computer that analyzes an amplitude of the signal waveform and then compares the amplitude to a database to determine the concentration of ions implanted in the material. Alternatively, the computer determines an area covered by the signal waveform, and then compares the
35 area to a database to determine the concentration of ions

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implanted in the material. In typical embodiments, the excitation sub-pulses and the probe pulse are overlapped in time in the region, and the photodetector has a bandwidth of less than 1 MHz.

5 Another apparatus that carries out the method of the invention includes a single laser and a beam-delivery system that includes a diffracting mask that separates the laser pulse into at least two excitation sub-pulses and a probe pulse. The system also includes a lens that
10 focuses and overlaps the two excitation sub-pulses and the probe pulse on the sample. In this embodiment, the sub-pulses form a grating pattern that initiates a time-dependent response in the region and the probe pulse diffracts off the region to generate a time-dependent
15 signal beam.

The above-described method and apparatus have many advantages when compared to conventional techniques for measuring the concentration of implanted ions. In general, FWM is an accurate, quantitative method for
20 determining the concentration of ions implanted in both semiconductor substrates and thin films. The method is all-optical, non-contact, and non-destructive, and can therefore measure semiconductor materials used in actual devices (i.e., production samples), rather than monitor
25 samples. This information can then be used by manufacturers to improve both the yield and performance characteristics of microelectronic devices containing these materials. In addition, the single-laser apparatus for making FWM measurements generates signal waveforms
30 having very high signal-to-noise ratios and the apparatus has a large dynamic range of measurement. This apparatus accurately measures samples, such as silicon wafers implanted with boron ions at low energies and concentrations, that in the past have been difficult to
35 measure with conventional instrumentation, such as those

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using two lasers. Moreover, this instrument is compact, easily automated, has very few optical elements, and is relatively inexpensive to manufacture. Since the concentration of implanted ions can be measured in this way, it is not necessary to determine the waveform's time dependence. This signal amplitude can be measured with simple optical and electrical components (e.g., low-bandwidth photodetectors and analog-to-digital converters) that are typically low-cost and commercially available.

Another advantage is that the phase mask simplifies the alignment of the excitation and probe laser beams and also eliminates the need for additional beam-delivery optics, such as additional lenses and beam splitters, that are normally required for FWM experiments. The number of required optical elements is even further reduced in embodiments where the phase mask diffracts an incident laser pulse to form both the excitation sub-pulses and the probe pulse.

Measurements with the above-mentioned apparatus are made rapidly (typically requiring only a few seconds) and with high spatial resolution (typically using a probe beam having a spot size of about 50 microns or less). Thus, small features of the sample, such as a small-scale test site of a microelectronic device or an area near a wafer's edge, can be easily measured. Moreover, the above-mentioned apparatus can be incorporated into a facile, compact, easy-to-use instrument that can be employed in a microelectronic-device fabrication facility. The instrument, for example, can be attached to a production tool and used to make *in situ* measurements of an ion-implantation process.

Still other advantages will be apparent from the following detailed description, and from the claims.

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Brief Description of the Drawings

Fig. 1 is a schematic drawing of the FWM method;

Fig. 2 is a graph of a signal measured during FWM with a single-laser optical system;

5 Figs. 3A-3B are graphs of the signal waveform amplitude (in mV) vs. the ion implant concentration measured from a set of silicon wafers implanted with different concentrations of boron ions at 3 and 5 keV;

Fig. 4 is a schematic drawing of a single-laser
10 optical system for measuring the concentration of ions implanted in a sample using FWM; and

Fig. 5 is a drawing of a single laser beam being diffracted to form two excitation sub-pulses and a probe pulse.

15

Detailed DescriptionMethod for Measuring Ion Implantation Concentration with FWM

Referring to Fig. 1, the concentration of ions implanted in a sample 10 (e.g., a silicon wafer) is
20 measured with an optical, laser-based technique called four-wave mixing (FWM). Applicants have described the use of related laser-based techniques, called impulsive stimulated scattering (ISS) and impulsive stimulated thermal scattering (ISTS), to measure other material
25 properties in MEASUREMENT OF MATERIAL PROPERTIES WITH OPTICALLY INDUCED PHONONS (U.S. Patent 5,633,711); SIMPLIFIED DEVICE AND METHOD FOR TIME-RESOLVED OPTICAL MEASUREMENTS (U.S.S.N. 08/377,310; filed 1/24/95); METHOD AND DEVICE FOR MEASURING FILM THICKNESS (U.S.S.N.
30 08/783,046; filed 6/15/96); IMPROVED METHOD AND APPARATUS FOR MEASURING MATERIAL PROPERTIES USING TRANSIENT GRATING SPECTROSCOPY (U.S.S.N. 08/885,555; filed 6/30/97); and METHOD AND APPARATUS FOR MEASURING THE CONCENTRATION OF IONS IMPLANTED IN SEMICONDUCTOR MATERIALS (U.S.S.N.
35 08/885,786; filed 6/30/97), all of which are incorporated

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herein by reference.

In FWM, a pair of optical excitation sub-pulses 12', 12'' from a laser (not shown in the figure) separated by an angle θ are overlapped in time and space 5 in a region on the sample's surface. Interference between the overlapped sub-pulses 12', 12'' forms a spatially varying "grating" pattern 15 containing alternating "light" (constructive interference) 17 and "dark" (destructive interference) 19 regions. The sample 10 10 absorbs radiation in the light regions 17, but not in the dark regions 19 of the grating pattern 15. The absorbed radiation initiates a time-dependent response characterized by an amplitude that depends on the concentration of the ions implanted in the sample 10. 15 This response is measured by irradiating a region near the grating pattern 15 with a probe pulse 20 generated by the same laser that generates the excitation sub-pulses 12', 12''. The probe pulse 20 is overlapped in time and space with these sub-pulses on the sample's surface. 20 This means that prior to irradiating the sample, the distance traveled by the excitation sub-pulses and the probe pulse after leaving the single-laser source is roughly equivalent. When these three pulses are overlapped in this way, the probe pulse is partially 25 reflected to form a reflected beam 20'', and partially diffracted to form a pair of signal beams 25', 25'' that are the +1 and -1 diffracted orders. One or both of the signal beams 25', 25'' is detected with a photodetector (not shown in the figure) to generate a signal waveform. 30 The amplitude of the signal waveform is then analyzed to determine the concentration of the implanted ions.

The excitation sub-pulses 12', 12'' typically have a duration of between 0.3 - 0.7 nanoseconds (i.e., $0.3 - 0.7 \times 10^{-9}$ seconds), an energy of about 2 35 microjoules/pulse, and a wavelength that is partially

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absorbed by the sample. For silicon, the wavelength is typically in the visible spectral region (e.g., 532 nm). Since it is generated with the same laser, the probe pulse has the same wavelength and duration as the
5 excitation pulse. The energy of the probe pulse is typically between 0.25 and 1.0 microjoules.

FWM generates a response in the sample when the excitation radiation has an energy that is above the band gap of the sample (for silicon, this is about 1.1 eV, an
10 energy that corresponds to an optical wavelength of or 900 nm). Without being bound to any theory, it appears that in this case the excitation pattern in FWM generates excited-state charge carriers (e.g., electron-hole pairs) in the light regions, but not the dark regions of the
15 grating pattern. The density of charge carriers depends on the concentration of ions implanted in the sample. Once generated, the charge carriers have a finite lifetime and recombine with a time constant on the order of several nanoseconds. During this period the sample's
20 refractive index in the light regions is temporarily changed relative to the refractive index in the dark regions. This results in a spatially periodic variation in refractive index (i.e., a phase grating) that diffracts probe radiation impinging on the sample during
25 the lifetime of the charge carriers. The diffraction efficiency is highest immediately after the charge carriers are formed, and thus the probe pulse is arranged to impinge on the sample at essentially zero time delay (i.e., the excitation sub-pulses and probe pulse are
30 overlapped in time). A higher concentration of implanted ions results in a larger number of excited charge carriers and, consequently, a greater difference in refractive index between the light and dark regions of the grating pattern. This, in turn, increases both the
35 diffraction efficiency of the phase grating and the

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intensity of the diffracted probe beam.

Fig. 2 shows a signal waveform 30 measured during FWM from a boron-implanted silicon wafer. The film was implanted with an average concentration of approximately 5 $0.5 \times 10^{14} \text{ cm}^{-3}$ boron ions at an energy of about 20 keV. Measurements were made with excitation sub-pulses having a wavelength of 532 nm, a duration of about 0.5 nanoseconds, and an energy of about 2.0 microjoules/sub-pulse. The sub-pulses were generated by 10 frequency-doubling the fundamental output from a Nd:YAG laser, and then passing this output through a phase mask (described in more detail with reference to Fig. 4). The probe pulse was generated by the same laser, and had an 15 length traveled by the excitation and probe pulses was roughly identical. The signal waveform was measured with a photodetector and analog-to-digital converter that in combination have a bandwidth of about 1 GHz.

As is clear from the data, the signal waveform 30 20 rises rapidly and then decreases in intensity to form a spike having an asymmetric shape. The full-width half-maximum (FWHM) of the spike is roughly equal to the duration of the excitation and probe pulses (about 0.5 ns). The amplitude of the signal waveform, shown as 25 being about 575 mV, depends on the concentration of ions implanted in the silicon sample ($0.5 \times 10^{14} \text{ cm}^{-3}$ in this case). The signal waveform also includes an oscillatory component 32 that is due to an electronic "ringing" in the photodetector. Although measured in this experiment 30 with a relatively high-bandwidth detection system (1 GHz), the amplitude of the waveform 30 could also be extracted with a much simpler system, e.g., a photodetector and analog-to-digital converter with a bandwidth of less than 1 MHz.

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Figs. 3A and 3B show how the amplitude of the signal waveform varies with the concentration of implanted ions. In these experiments, electronic responses were measured from a set of 100-mm diameter silicon wafers implanted with boron ions ranging from 1.5 - $3.0 \times 10^{15} \text{ cm}^{-3}$. The implant energies for Figs. 3A and 3B were, respectively, 3 and 5 keV. The data were measured from a center point of each wafer using FWM and the same single-laser instrument described above. The data show that the signal waveform amplitude increases systematically with the concentration of implanted ions for each of the implantation energies. Similar dependencies of signal waveform amplitude on ion concentration were observed with boron, arsenic, oxygen, and phosphorous ions implanted in silicon wafers at energies ranging from 1-1000 keV and concentrations ranging from 1.0×10^{12} to $1.0 \times 10^{16} \text{ cm}^{-3}$. Typically, silicon wafers with ions implanted at concentrations of $1.0 \times 10^{12} \text{ cm}^{-3}$ display signal levels of a few hundred mV, while wafers implanted with ions implanted at concentrations of $1.0 \times 10^{16} \text{ cm}^{-3}$ have signal levels of about 1000 mV.

In a typical embodiment, data like that shown in Figs. 3A-3B is measured from a set of samples which vary systematically in one or more properties (e.g., concentration), and then stored in a database on a computer. The dependence of signal amplitude on concentration may depend on process conditions such as implant species, temperature, current, and orientation of the wafer relative to the incident ion beam. Thus, separate databases, each containing a data set similar to that shown in Figs. 3A-3B, is typically generated for each process condition. To do this, the data can be measured from a set of test samples having a systematically varying concentration of implanted ions

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whose concentrations are verified with electrical testing instruments, such as a 4-point probe. During an actual measurement, the amplitude of a signal waveform is measured with FWM as described above, and then compared
5 to a value in the appropriate database. This determines the concentration of ions implanted in a sample during an actual fabrication process.

Apparatus for Determining Ion Implant Properties
Using FWM

10 Fig. 4 shows an optical system 50 for measuring the properties of an ion-implanted sample 10 using FWM. The system 50 includes a single laser 52, such as a Nd:YAG laser, that generates a pulse 49 having the optical properties described above. Once generated, the
15 pulse 49 irradiates a beamsplitter 51 that partially reflects a small portion (e.g. typically 5-15%) of the pulse 49 to form a probe pulse 20, and transmits the remainder of the pulse 49 to form the excitation pulse 12. The excitation pulse 12 then irradiates a mirror 53
20 that reflects it through a first collimating lens 60 and then through a neutral-density filter 61 used for adjusting the pulse energy. The pulse is then focused onto a phase mask 62 with a cylindrical lens 64. The phase mask 62 includes a series of patterns 66, each of
25 which is capable of generating a different grating pattern 15 on the sample 10. The appropriate pattern is selected to produce the desired grating pattern on the sample. After selecting the appropriate pattern 66 on the phase mask 62, the excitation pulse 12 is diffracted
30 into two sub-pulses 12', 12'' that diverge at an angle θ determined by the selected pattern 66. The diverging sub-pulses 12', 12'' are collected with a first imaging lens 70 that focuses and overlaps them onto the surface of the sample 10 to form the grating pattern 15. The
35 first imaging lens 70 is positioned so that the grating

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pattern 15 has one half of the periodicity of the pattern 66 on the phase mask 62. Different grating patterns can be formed simply by translating the phase mask 62 so that a new pattern is irradiated with the incident excitation pulse 12.

Note that the probe pulse 20 is split prior to the collimating lens 60, and thus it spatially diverges over its optical path length, thereby allowing the pulse 20 to be focused to a smaller spot on the sample. A portion 20' of the pulse 20 is reflected by a beam-splitter 65 and detected with a trigger photodetector 67 to generate an electrical pulse for triggering a data-acquisition system. The portion of the probe pulse 20 that passes through the beam-splitter 65 is reflected by a pair of mirrors 21a, 21b and then focused on the grating pattern 15 with a second spherical lens 71 to measure the ion-implanted sample 10. The spacing between the mirrors 21a, 21b is adjusted so that the optical path lengths of the excitation sub-pulses (12' and 12'') and the pulse probe 20 are approximately equal. This overlaps these pulses in time on the sample's surface, thereby ensuring that the maximum signal amplitude (which occurs at zero delay of the probe pulse) will be measured.

Once irradiated, the sample diffracts a portion of the probe pulse 20 to form a signal beam 25'. A beam-stop 80 blocks a reflected portion of the probe pulse 20''. A second imaging lens 76 collects the signal beam 25' and focuses it into a high-speed (e.g., 1 GHz) photodetector 82. This generates a light-induced electrical signal which is then passes through an analog-to-digital converter 83 to produce a digital signal that is analyzed by a computer 84 which is programmed with an analysis algorithm to determine the concentration of ions implanted in the sample. The analysis algorithm is stored in a computer readable

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medium from where it is loaded in executable form into RAM memory of the computer.

The spatial dimensions of the excitation sub-pulses 12', 12'' and probe pulse 20 focused onto the sample are chosen to maximize the amplitude of the signal waveform. The excitation sub-pulses are typically overlapped to form an elliptical grating pattern with the long and short axes of the ellipse being roughly 150 and 25 microns, respectively. The distance between light and dark regions in the grating pattern is typically between 5 and 15 microns. The probe pulse is typically focused to a round spot that lies completely within the grating pattern. For example, the probe pulse can be focused to a round spot with a diameter of less than 25 microns.

15 Other Embodiments

Other embodiments are within the scope of the above-described method and apparatus. For example, different optical systems, such as one including: 1) a different lens configuration than that described above; 20 2) an amplitude mask in place of the phase mask; or 3) a beamsplitter in place of the phase mask, can be used. Fig. 5 shows another optical configuration 85 for generating both excitation sub-pulses 12', 12'' and a probe pulse 13 from a single laser beam. In this case, a single pulse 12 from a laser (not shown in the figure) 25 irradiates a pattern 66 on a phase mask 62 as described above. The pattern is chosen so that a majority (e.g., 85%) of the pulse 12 is diffracted into the +/-1 orders to form the excitation sub-pulses 12', 12''. The portion 30 of the incident pulse 12 diffracted into the +2 (or -2) order forms the probe pulse 13. The excitation sub-pulses 12', 12'' and probe pulse 13 are collected with a single lens (such as lens 70 in Fig. 4) and then focused onto the sample as described above to measure the 35 ion implantation concentration. In still other

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embodiments, a mirror may be inserted into the optical system shown in Fig. 5 to reflect the probe pulse through the lens and toward the sample.

In another optical system, described in IMPROVED
5 METHOD AND APPARATUS FOR MEASURING MATERIAL PROPERTIES
USING TRANSIENT GRATING SPECTROSCOPY (U.S.S.N.
08/885,555; filed 6/30/97), three sub-pulses, rather than
two, are used to excite the sample in a FWM arrangement.
In this optical system, the three sub-pulses are equally
10 spaced in a linear fashion (i.e., the center, right, and
left beams) prior to being imaged onto the sample. When
focused with a lens, the center beam propagates down a
central optical axis of a beam-delivery system, while the
right and left beams converge toward the same spot at the
15 same angle but on opposite sides of the center beam. The
beams are overlapped on the sample to form the grating
pattern that excites charge carriers in the sample.

In general, any optical system for performing ISS,
ISTS or FWM is suitable to measure the concentration of
20 implanted ions using the method described above.
Likewise, other lasers that have suitable optical
properties can be used in place of the Nd:YAG laser
described above.

In other embodiments, FWM measurements can be
25 performed using two synchronized lasers in place of the
single laser described above. Each of the synchronized
lasers generates a short (e.g., 0.5 ns) optical pulse,
one which represents the excitation pulse, and the other
laser which represents the probe pulse. As described
30 above, the resulting two laser beams are oriented so that
pulses are overlapped in time on the sample's surface.

In still other embodiments, the system uses
multiple probe pulses, each of which is delayed in of
time relative to the others, to measure a decay time
35 constant of the excited charge carriers. For example,

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the system uses a first probe pulse to irradiate the sample at zero time delay, and then it uses a second pulse, which is mechanically delayed, to irradiate the sample a few nanoseconds later. The first pulse will
5 produce a signal having a given amplitude and the second, later pulse will produce a signal having a lower amplitude. The change in amplitude represents a decay process (e.g. exponential decay process) that can be characterized by a time constant. The computer analyzes
10 the two signal waveforms generated by the two probe pulses and determines the decay time constant for the charge carriers. Since we have found that there is a correlation between the decay time constant and the energy at which the ions were implanted into the sample,
15 the computer then uses the decay time constant to determine the implantation energy, possibly employing stored tables of empirically derived data to perform a translation from one to the other.

In still other embodiments, a signal waveform is
20 measured as described in the parent patent application (U.S.S.N. 08/885,786), i.e., using two independent lasers. The decay time constant of the waveform can be computed and processed in the manner described above to determine the energy at which the ions were implanted.

25 In still other embodiments, the apparatus can be modified to additionally measure the thickness of thin oxide (i.e. SiO_2) films that are grown on a silicon sample when the sample is subjected to high temperatures. For example, the computer can analyze the reflected probe
30 beam (20" in Fig. 4) in the same way that reflected beams are analyzed in standard ellipsometers or reflectometers. This analysis permits simultaneous determination of ion implantation concentration and oxide film thickness. In other embodiments, sets of excitation sub-pulses having
35 different wavelengths (e.g. 532 nm and 1064 nm) can be

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generated and used to simultaneously generate grating patterns in the sample being measured. In that case, the intensity of the diffracted signal beams can be analyzed to determine the species of the implanted ions. In other
5 embodiments, the apparatus can be modified to simultaneously measure physical processes that result in phase gratings (e.g., excited charge carriers) and surface ripple (e.g., thermal processes) in the sample. For example, thermal processes that generate surface
10 ripple in the sample will have a time dependence and diffraction efficiency that varies with the phase mask pattern (and thus the spatial periodicity of the grating pattern) used during the measurement. In contrast, the time dependence of non-diffusive processes, such as
15 charge carrier lifetimes, is independent of the phase mask and grating patterns. Thus, these processes can be determined independently by measuring a sample at a number at different phase mask patterns. In still other embodiments, a probe laser that generates a pulse having
20 a long duration (e.g., several microseconds) relative to the lifetime of the charge carriers can be included in the optical system. This way, measurements can simultaneously be performed with probe pulses having different time durations and peak intensities. In still
25 other embodiments the polarization of the diffracted probe pulse can be analyzed to determine certain properties of the sample, such as oxide film thickness and implant species.

There also exists other embodiments for processing
30 the signal waveform to determine the concentration of implanted ions. For example, the signal waveform can be processed by plotting it and then determining the area underneath the plot. This area is then compared to values in a database to determine the ion concentration.
35 In other embodiments, the signal waveform is fit to a

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function to determine its amplitude, which is then processed as described above. In still other embodiments, mathematical algorithms, such as algorithms based on kinetic modeling of a charge-carrier system, can
5 be developed to relate the concentration of implanted ions to an amplitude of the signal waveform. Such algorithms would obviate the need for a database to determine the ion concentration.

In still other embodiments, laser beams that are
10 not pulsed (i.e., continuous-wave excitation and probe beams) are used in the FWM arrangement to determine the concentration of ions in the sample. In this case, the amplitude of the diffracted signal beam correlates to the ion concentration. The signal beam, for example, may be
15 detected using standard detection techniques known in the art, such as lock-in detection.

Still other embodiments are within the scope of the following claims:

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What is claimed is:

1. A method for determining a concentration of ions implanted in a material, comprising the steps of:
generating at least two excitation laser
5 sub-pulses and a probe pulse from a single pulse emitted from a laser;
irradiating a region of the material with a grating pattern, formed by overlapping at least two excitation laser sub-pulses, to initiate a time-dependent
10 response in the region;
diffracting a probe laser pulse off the region to generate at least one time-dependent signal beam;
detecting at least one time-dependent signal beam to generate a signal waveform; and
15 processing the signal waveform to determine the concentration of ions implanted in the material.
2. The method of claim 1, wherein the processing step includes determining a property of the signal waveform and then analyzing the property to determine the
20 concentration of ions implanted in the sample.
3. The method of claim 2, wherein the property is an amplitude of the signal waveform.
4. The method of claim 2, wherein the processing step further includes comparing the property of the
25 signal waveform to a database.
5. The method of claim 4, wherein the comparing step further includes comparing the property of the signal waveform to a database that correlates properties of previously measured signal waveforms to concentrations
30 of ions implanted in materials to determine the concentration of ions implanted in the material.

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6. The method of claim 5, wherein the property of the signal waveform is an amplitude.

7. The method of claim 1, wherein the processing step further includes analyzing the property with a
5 mathematical algorithm to determine the concentration of ions implanted in the material.

8. The method of claim 1, wherein the processing step includes digitizing the signal waveform to generate a data set and then determining an amplitude of the
10 signal waveform at a point in time by selecting a value from the data set.

9. The method of claim 1, wherein the processing step includes determining an area covered by a plot of the signal waveform.

15 10. The method of claim 9, wherein the processing step further includes comparing the area to a database.

11. The method of claim 10, wherein the comparing step further includes comparing the area to a database that correlates the area with the concentration of ions
20 implanted in a material to determine the concentration of ions implanted in the material.

12. The method of claim 1, wherein the material contains silicon.

13. The method of claim 12, wherein the material
25 is a polysilicon film.

14. The method of claim 12, wherein the material is a silicon wafer.

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15. The method of claim 1, wherein an ion implanted in the material is an ion of an atom selected from the group consisting of arsenic, argon, boron, oxygen and phosphorous atoms.

- 5 16. A method for determining a concentration of ions implanted in a material, comprising the steps of:
 generating a single laser pulse;
 passing the laser pulse through a diffracting mask
 to form at least two excitation sub-pulses and at least
10 one probe pulse;
 irradiating a region of the material with a grating pattern, formed by overlapping at least two excitation laser sub-pulses to initiate a time-dependent response in the region;
15 diffracting the probe laser pulse off the region to generate at least one time-dependent signal beam;
 detecting at least one time-dependent signal beam to generate a signal waveform; and
 processing the signal waveform to determine the
20 concentration of ions implanted in the material.

17. The method of claim 1, wherein the processing step includes determining a property of the signal waveform and then processing the property to determine the concentration of ions implanted in the sample.

- 25 18. The method of claim 17, wherein the property is an amplitude of the signal waveform.

19. The method of claim 17, wherein the processing step further includes comparing the property of the signal waveform to a database.

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20. The method of claim 19, wherein the comparing step further includes comparing the property of the signal waveform to a database that correlates properties of previously measured signal waveforms to concentrations
5 of ions implanted in materials to determine the concentration of ions implanted in the material.

21. An apparatus for determining a concentration of ions implanted in a semiconducting material, comprising:

10 a laser for generating an excitation laser pulse and a probe laser pulse;

a first beam-delivery system for separating the excitation laser pulse into at least two excitation sub-pulses and then irradiating a region of the material
15 with a grating pattern formed by overlapping at least two excitation sub-pulses to initiate a time-dependent response in the region;

a second beam-delivery system for delivering the probe pulse to the sample such that the probe pulse
20 diffracts off the region to generate a time-dependent signal beam;

a photodetector for detecting the time-dependent signal beam to generate a signal waveform; and

a processor for processing the signal waveform to
25 determine the concentration of ions implanted in the material.

22. The apparatus of claim 21, wherein the first beam-delivery system includes a diffracting mask that separates the excitation laser pulse into at least two
30 sub-pulses.

23. The apparatus of claim 21, wherein the diffracting mask is a phase mask or an amplitude mask.

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24. The apparatus of claim 21, wherein the processor is a computer that analyzes an amplitude of the signal waveform and compares the amplitude to a database to determine the concentration of ions implanted in the material.

25. The apparatus of claim 21, wherein the processor is a computer that determines an area covered by the signal waveform and compares the area to a database to determine the concentration of ions implanted in the material.

26. The apparatus of claim 21, wherein the excitation sub-pulses and the probe pulse are overlapped in time in the region.

27. The apparatus of claim 21, wherein the photodetector has a bandwidth of less than 1 MHz.

28. An apparatus for determining a concentration of ions implanted in a semiconducting material, comprising:

- a laser for generating a laser pulse;
- 20 a beam-delivery system comprising a diffracting mask that separates the laser pulse into at least two excitation sub-pulses and a probe pulse, and a lens that focuses and overlaps at least two excitation sub-pulses and the probe pulse on the sample so that the excitation
- 25 sub-pulses form a grating pattern that initiates a time-dependent response in the region and the probe pulse diffracts off the region to generate a time-dependent signal beam;
- a photodetector for detecting the time-dependent
- 30 signal beam to generate a signal waveform; and

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a processor for processing the signal waveform to determine the concentration of ions implanted in the material.

29. The apparatus of claim 28, wherein the
5 diffracting mask is a phase mask or an amplitude mask.

30. The apparatus of claim 28, wherein the
processor is a computer that analyzes an amplitude of the
signal waveform and compares the amplitude to a database
to determine the concentration of ions implanted in the
10 material.

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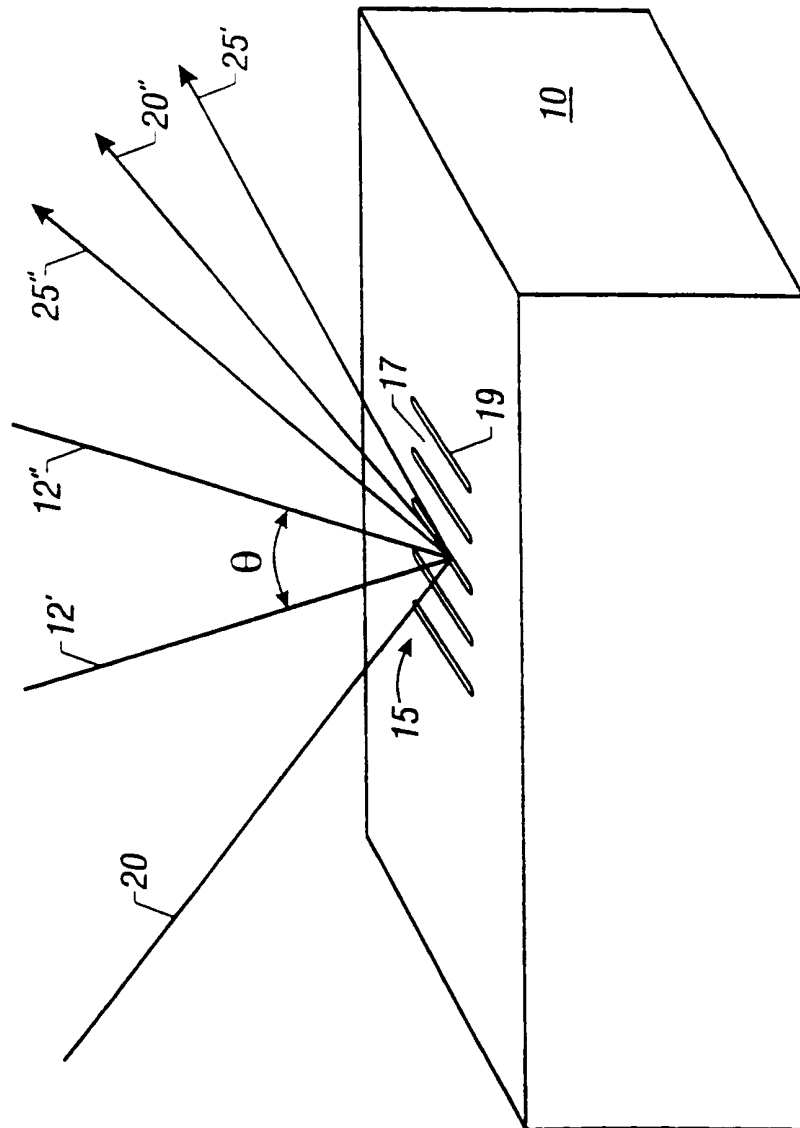


FIG. 1

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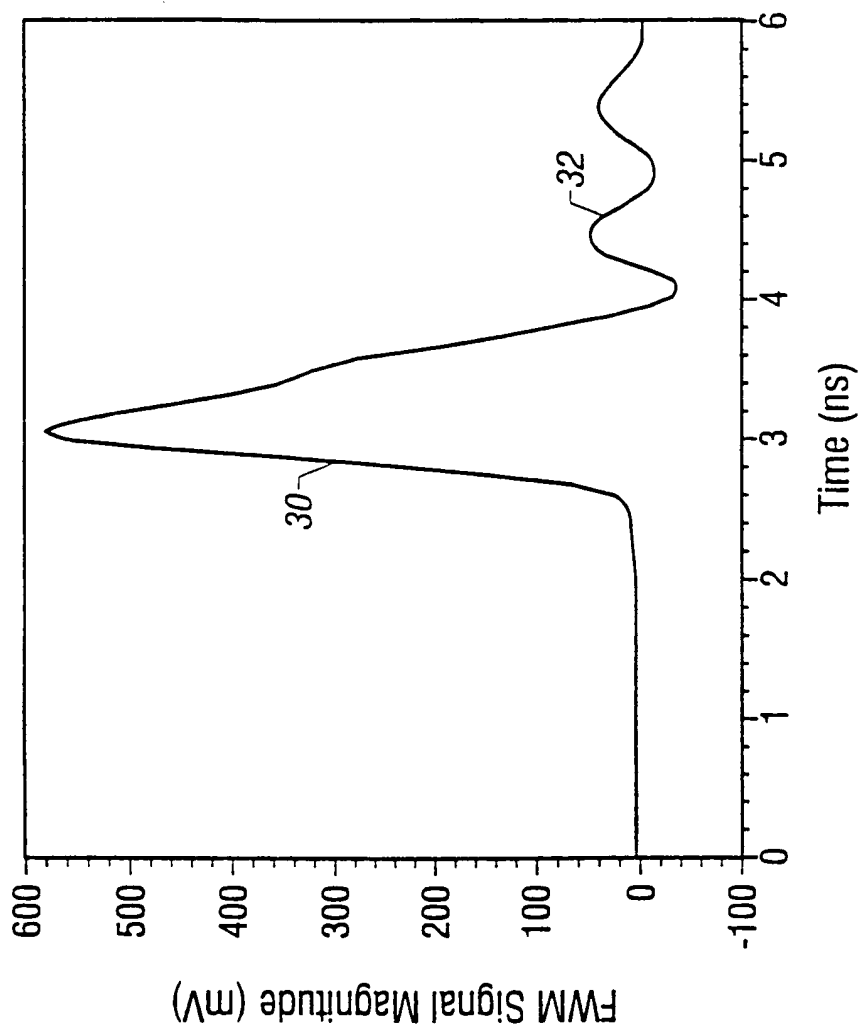


FIG. 2

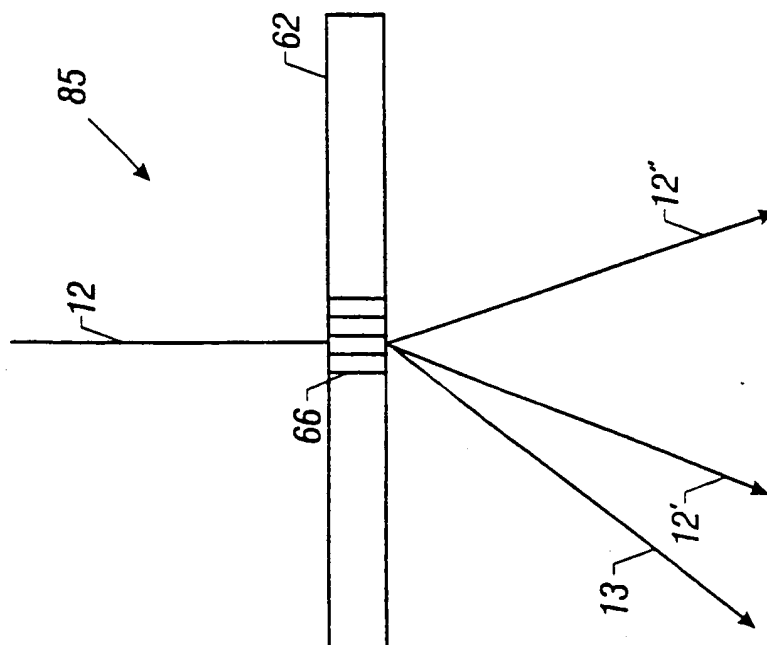


FIG. 5

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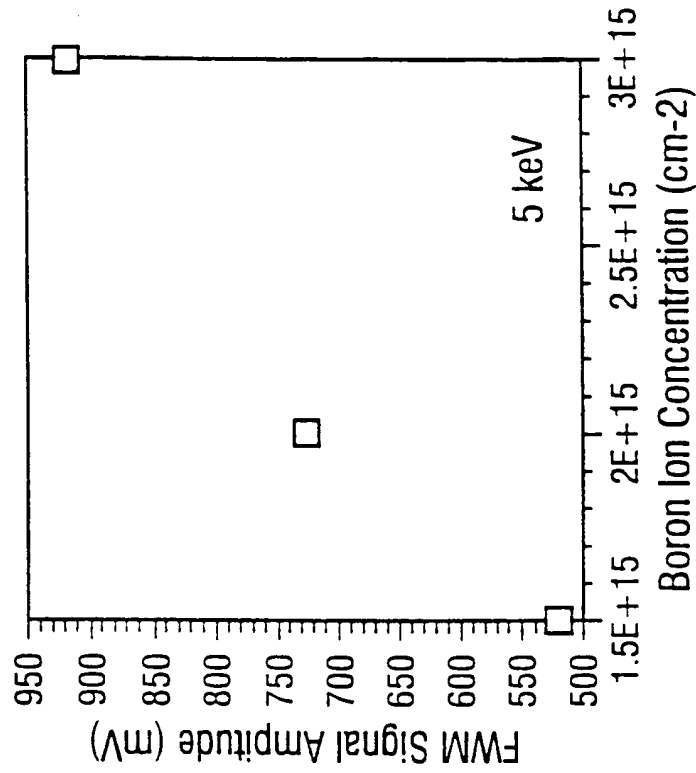


FIG. 3B

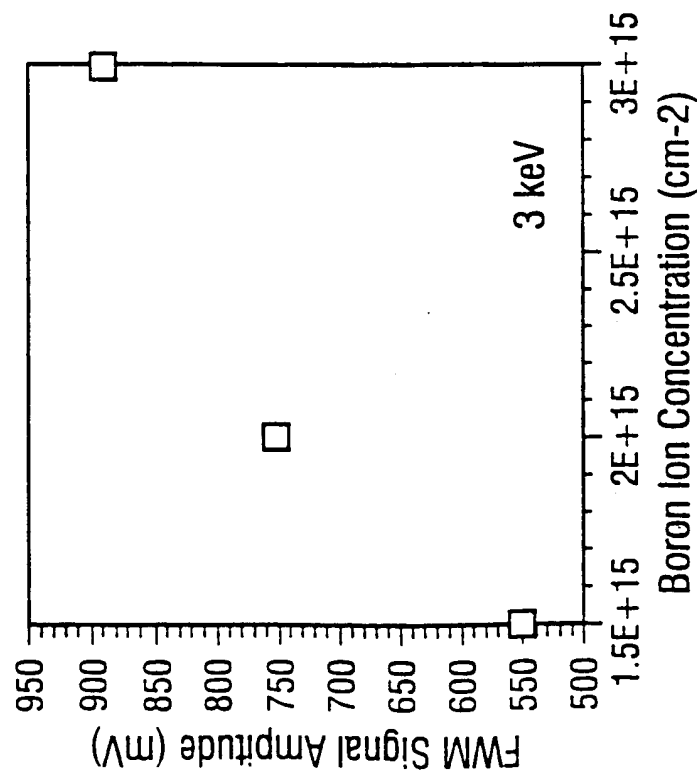


FIG. 3A

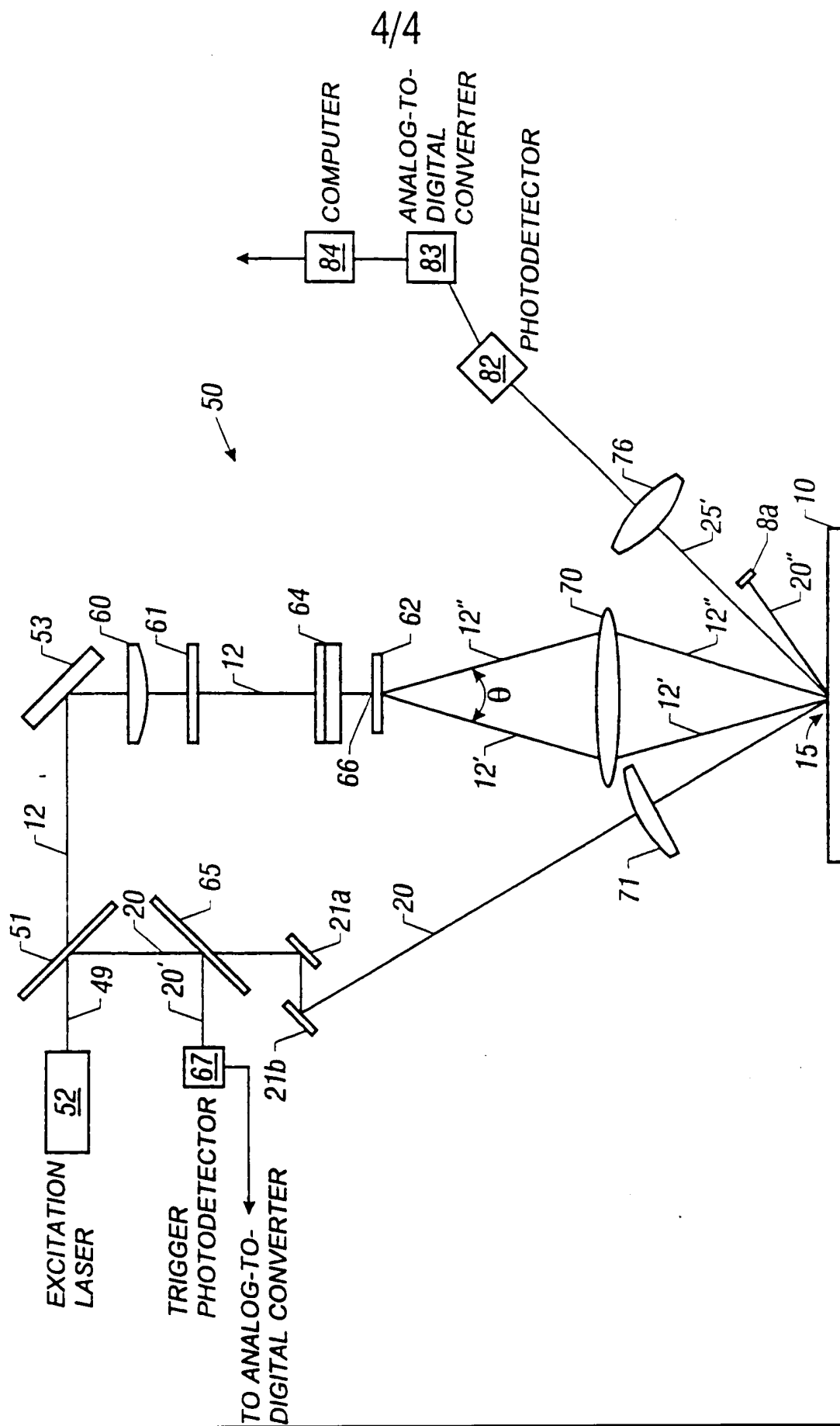


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/13473

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G01B 09/02

US CL : 356/432

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/432, 432T, 354, 359

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS:excitation, probe, diffraction grating

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|-----------|--|-----------------------|
| A,P | US 5,734,470 A (ROGERS et al) 31 March 1998 (31.03.98), entire document | 1-30 |

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

| | |
|---|--|
| * Special categories of cited documents: | *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention |
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| *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) | *A* document member of the same patent family |
| *O* document referring to an oral disclosure, use, exhibition or other means | |
| *P* document published prior to the international filing date but later than the priority date claimed | |

Date of the actual completion of the international search

14 AUGUST 1998

Date of mailing of the international search report

03 SEP 1998

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